NEUROMUSCULAR DETERMINANTS OF UNILATERAL JUMP PERFORMANCE IN SOCCER PLAYERS ARE DIRECTION-SPECIFIC

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ABSTRACT

Purpose: To investigate differences in neuromuscular factors between elite and non-elite players, and to establish which factors underpin direction-specific unilateral jump performance. **Methods:** Elite (n=23; age, 18.1 ± 1.0 yrs; BMI, 23.1 ± 1.8 kg/m^2) and non-elite (n=20; age, 22.3 ± 2.7 yrs; BMI, 23.8 ± 1.8 kg/m^2) soccer players performed three unilateral countermovement jumps (CMJs) on a force platform in the vertical, horizontal-forward and medial directions. Knee extension isometric maximum voluntary contraction (iMVC) torque was assessed using isokinetic dynamometry. Vastus lateralis fascicle length and angle of pennation (AoP), and quadriceps femoris muscle volume (M_{vol}) and physiological cross sectional area (PCSA) were assessed using ultrasonography. Vastus lateralis activation was assessed via electromyography. **Results:** Elite soccer players presented greater knee extensor iMVC torque (365.7±66.6 vs. 320.1±62.6 N·m; P=0.045), M_{vol} (2853±508 vs. 2429±232 cm^3, P=0.001) and PCSA (227±42 vs. 193±25 cm^2, P=0.003) than non-elite. In both cohorts, unilateral vertical and unilateral medial CMJ performance correlated with M_{vol} and PCSA (r≥0.310 P≤0.043). In elite soccer players, unilateral vertical and unilateral medial CMJ performance correlated with upward phase vastus lateralis activation, and AoP (r≥0.478, P≤0.028). Unilateral horizontal-forward CMJ peak vertical power did not correlate with any measure of muscle size or activation but correlated inversely with AoP (r=-0.413; P=0.037). **Conclusions:** Whilst larger and stronger quadriceps differentiated elite from non-elite players, relationships between neuromuscular factors and unilateral jump performance were shown to be direction-specific. These findings support a notion that improving direction-specific muscular power in soccer requires improving a distinct neuromuscular profile.

INTRODUCTION

Powerful efforts are performed frequently during elite soccer match-play [1] and often determine the outcome of competitive games [2]. Elite soccer players have been shown to out-perform non-elite soccer players during maximal unilateral countermovement jumps (CMJs) in the vertical, horizontal-forward and medial directions [3], thus suggesting unilateral CMJ capabilities in different directions may be important determinants of elite soccer playing status. An analysis of the kinetic, kinematic and electromyographic variables suggested that unilateral CMJs in different directions assess independent lower-limb power qualities in soccer players [3]. However, no attempt has been made to investigate the neuromuscular factors underpinning direction-specific (soccer-associated) CMJ performance. Such information could be used to inform the neuromuscular factors that should be considered when prescribing the specific detail of elite soccer maximal power related assessment and development protocols.

A series of interrelated neuromuscular factors contribute to maximal muscular power production, which is defined by the force-velocity relationship [4]. Muscle volume is the product of muscle physiological cross-sectional area (representative of the maximum force-generating capacity of that muscle) and fascicle length (a major determinant of muscle contraction velocity) [5]. Therefore, as power is the product of force x velocity, it follows that muscle volume should represent a major determinant of maximum muscle power. Indeed, quadriceps femoris muscle volume has been shown to be strongly related to mean power produced during bilateral vertical CMJs in adults and children ($r^2 = 0.9$) [6], and moderately related in male children alone ($r^2 = 0.3$) [7]. Nonetheless, bilateral vertical CMJ performance is not a determinant of elite soccer playing status; instead, unilateral CMJ performance in different directions has been shown to differentiate between elite and non-elite soccer players [3]. As unilateral CMJs in different directions require distinct vertical peak power [3,8] and resultant take-off velocity [3] capabilities, such tasks may be underpinned by neuromuscular factors specific to the direction of the propulsion. However, the contribution of muscle volume and its individual components (physiological cross sectional area and fascicle length) to unilateral CMJ performance in different directions remains unknown.

In addition to fascicle length, fascicle pennation angle (the angle at which the fascicles insert into the aponeurosis) is also thought to influence maximal power. The fascicle pennation angle is thought to be determined by the number of sarcomeres arranged in parallel and, thus, the muscle fibre cross sectional area [9]. A larger fascicle pennation angle would allow more contractile material to attach to the aponeurosis, thus increasing the whole muscle physiological cross sectional area (PCSA) and enabling the muscle to produce more force [9,10]. Thus, a greater fascicle pennation angle should lead to an increase in force output, although there is a concomitant reduction in the force resolved at the tendon due to the oblique line of pull of the fascicles [9,10]. Furthermore, fascicle pennation angle correlates inversely with the rate of force development (RFD) [11] and has a negative influence on muscle contractile velocity [9,12]. However, the contribution of fascicle pennation angle to sport-specific actions such as unilateral CMJs in different directions, remains unknown.

Maximal muscular power is not only determined by muscle architecture and size, but also by the ability to recruit motor units and activate all of the fibres in the specific muscles involved in the movement [4]. Whilst it has been established that unilateral [3] and bilateral CMJs in different directions require different muscle activation strategies [13,14], the role of muscle activation in determining direction-specific unilateral CMJ performance is not known.

While identifying the neuromuscular components that contribute to unilateral CMJ performance in each direction could allow the prescription of more specific training intervention strategies, understanding which neuromuscular factors determine soccer playing status could potentially inform talent selection and development protocols. Furthermore, if a specific neuromuscular component differentiates between soccer performance levels, it can be assumed that this quality is important for elite performance. However, no attempt has been made to compare the neuromuscular capabilities in elite and non-elite soccer players. Current soccer talent identification models may therefore, be limited.

Subsequently, the aims of our study were to: (1) investigate the differences in muscle strength, size, architecture and activation between elite and non-elite soccer players; and (2) determine the contribution of muscle size, architecture and activation to unilateral CMJ performance in different directions in elite and non-elite soccer players.

METHODS

Subjects

Forty-three male soccer players volunteered to take part in this study, which was approved by Liverpool John Moores University Ethics Committee and complied with the Declaration of Helsinki. Participants provided written informed consent prior to being assigned to one of two groups according to their level of competition. The elite soccer player group (n = 23, mean ± SD: age 18.1 ± 1.0 years; height 182.5 ± 7.3 cm; weight 77.2 ± 10.1 kg) included one goalkeeper, nine defenders, five midfielders and eight forwards from an English Premier League football academy, who regularly participated at U18 and U21 level. The non-elite soccer player group (n = 20, mean ± SD: age 22.3 ± 2.7 years; height 175.0 ± 5.8 cm; weight 72.9 ± 7.3 kg) included one goalkeeper, five defenders, six midfielders and eight forwards, who participated in at least one hour per week of competitive soccer (11-a-side or five-a-side), and one hour per week of soccer specific or fitness based training. Non-elite participants were excluded if they did not meet these inclusion criteria or had previously played soccer at academy, semi-professional, or professional level. All participants had been free of any injury to the lower body within the previous three months and had not previously sustained a serious knee or ankle injury which may be aggravated during testing procedures, or cause an adverse effect on performance. Participants were fully familiarised with all testing procedures in a separate session and were asked to complete a physical activity and health questionnaire prior to the study for screening purposes. This questionnaire allowed us to ascertain if each potential participant satisfied the specific inclusion and exclusion criteria.

Design

All participants attended the lab on two separate occasions with at least 72 hours between each session. The first session enabled the participants to be familiarised with the assessment protocol, which consisted of performing three unilateral CMJs in the vertical, horizontal-forward and medial directions on each leg, three repetitions of knee extension and knee flexion isometric maximal voluntary contractions (iMVCs), and ten successful repetitions of isometric rapid knee extension contractions [successful rapid isometric contractions were defined as contractions initiated from a stable baseline force (no pre-tension or visible countermovement) that reached 80% of their respective iMVC peak torque]. All CMJs were visually demonstrated to the participants by the investigator. This session was also used to determine the superior jumping leg [defined as the limb that produced the highest ground reaction force during a unilateral vertical CMJ]. During the second session, participants performed all CMJs, knee extension and knee flexion iMVCs, knee extension isometric explosive force assessments, and measurements of vastus lateralis muscle architecture, and quadriceps femoris muscle anatomical cross sectional area (using ultrasonography). Electromyographic (EMG) activity in the vastus lateralis and biceps femoris was measured throughout the CMJ and strength assessments. In order to minimise the influence of previous activity, the testing was performed at least 48 h following any high intensity multi-directional exercise which included any form of soccer match-play activity.

Methodology

Countermovement jumps.

On arrival at the laboratory for the second session, all participants had their height and body mass measured. Participants performed three trials of each CMJ type (with 60 seconds recovery between trials within a single CMJ type, and 180 s between jump types), thus performing a total of 18 CMJs (9 unilateral jumps on each leg). The exact methods for the performance and data analysis of unilateral CMJs has been explained in detail previously [3]. The key performance variables for the unilateral vertical CMJ were jump height (calculated from the impulse-momentum relationship derived take off velocity and equation of constant acceleration methods [15]) and peak vertical power (peak V-power). The key performance variables for horizontal-forward and medial CMJs were projectile range (calculated using equations of constant acceleration [16]), peak V-power, and peak horizontal-forward power (for horizontal-forward CMJs only) or peak medial power (for medial CMJs only). Projectile range was used as the criterion performance measure for horizontal-forward and medial CMJs as, unlike when measuring jump distance using a measuring tape, projectile range is not affected by airborne and landing technique and better represents the propulsive phase of the jump [17]. All peak power variables were allometrically scaled to body mass ($BM^{0.67}$) (Jaric et al., 2005).

Muscle Volume

Muscle volume was assessed by adapting a previously validated measurement [18]. With the participant in a relaxed seated position (knee joint angle at 90°), B-mode ultrasonography (MyLab 30 CV, Esoate Biomedica, Genoa, Italy) was used to locate the distal (lateral femoral condyle) and proximal (base of greater trochanter) ends of the femur, with the distance between both points providing the femur length. The anatomical cross-sectional area (ACSA) of the quadriceps was then measured at 40% of femur length (from the distal end) using ultrasound, and following a previously reported method [19]. Using the femur length, quadriceps femoris anatomical cross sectional area at 40% femur length, and a series of regression equations detailed elsewhere [18], the quadriceps femoris muscle volume (M_{vol}) was calculated [5]. To account for skeletal-dependent inter-individual variability, quadriceps femoris M_{vol} was also normalised to femur length and referred to as relative quadriceps femoris M_{vol}.

Muscle architecture

Vastus lateralis muscle architecture was measured at rest using ultrasonography with the participant in a relaxed seated position (knee joint angle at 90°). Once the origin and insertion of the vastus lateralis were identified, this enabled the lateral and medial boundaries of the muscle to be located at 50% of its length. The centre of the muscle was then marked on the skin with a permanent marker pen, and this location was used for all architectural measures. Muscle thickness, fascicle length (L_f), and pennation angle (θ_p) were measured at rest according the procedures described previously [5]. To account for skeletal-dependent inter-individual variability, L_f was also normalised to femur length and referred to as relative L_f.

Muscle strength

Knee extension and knee flexion iMVCs were assessed on an isokinetic dynamometer (Biodex 3, Medical Systems, Shirley, NY, USA) and analysed using AcqKnowledge data acquisition software (Biopac Systems Inc., Goleta, CA, USA). All measurements were performed on the superior jumping leg only. Muscle activation during these iMVCs was used to normalize the EMG data during the jump assessment protocol. Participants sat on the rigid chair with their hip angle set to 85° (supine position was equivalent to 180°) and strapped securely at the hip, chest and distal thigh with inextensible straps to minimise movement. The set-up and protocol for iMVCs has been described in detail previously [5] but the knee angle was fixed at 90° via goniometry for all assessments.

Following the iMVCs, participants were asked to perform ten isometric rapid knee extension contractions, each separated by a 20 s rest interval. This method has been explained in detail elsewhere [11,20]. Briefly, during each contraction, participants were instructed to extend their knee as 'fast and hard' as possible from a relaxed state for <1 s, while avoiding a countermovement and achieving ~80% quadriceps iMVF. The three contractions with the greatest peak rate of force development (RFD) were chosen for further analysis which consisted of measuring force output at 50, 100 and 150 ms after force onset, in addition to RFD from 0-50 ms, 50-100 ms, and 100-150 ms after force onset. The mean rapid force and RFD values from the three contractions were used for subsequent analysis. Force onsets were identified by manual identification according to guidelines proposed by Tillin and Colleagues [21].

The torque signal (for iMVCs and isometric explosive contractions) was interfaced with an analog-to-digital converter (Biopac Systems Inc., Goletta, USA), sampled at 2000 Hz with a PC using AcqKnowledge software (Biopac Systems Inc.) and low-pass filtered (10-Hz edge frequency).

Physiological cross sectional area

The physiological cross sectional area (PCSA) of the quadriceps femoris was calculated by dividing quadriceps femoris M_{vol} by vastus lateralis L_f [5].

Electromyography

During all CMJ and iMVC assessments, surface EMG activity was recorded from the vastus lateralis and biceps femoris muscles of the dominant lower limb using self-adhesive Ag/AgCl bipolar surface electrodes (2-cm inter-electrode distance, 1-cm circular conductive area; product 72000-S/25, Neuroline 720, Ambu, Denmark). The EMG signal was sampled simultaneously at a rate of 2000 Hz with ground reaction force data during jump assessments, and isokinetic dynamometry torque data during strength assessments. The exact methods for the recording and analysis of EMG has been explained in detail previously [3].

Antagonist muscle co-activation

To determine the extent of antagonist muscle co-activation during the knee extension iMVC, the average root mean squared EMG activity of the biceps femoris muscle over a 500ms epoch around peak torque was recorded during knee extension and knee flexion isometric maximal voluntary contraction. The ratio of antagonist co-activation during the knee extension iMVC was recorded as a percentage of the average root mean squared EMG activity of the biceps femoris during maximal knee flexion contraction.

Maximum quadriceps femoris muscle isometric torque

The torque produced by the hamstring muscle group during knee extension iMVC was estimated, assuming a linear relationship between torque and EMG activity [5]. Overall knee extensor corrected isometric maximal voluntary torque (iMVT) was calculated by the addition of the estimated antagonist torque during knee extension to the actual knee extension isometric maximal voluntary torque [5,22].

Quadriceps femoris muscle specific force

As the force transmitted from the quadriceps femoris muscle fibres to the tendon is reduced according to fascicle θ_p, a reduced PCSA of the quadriceps femoris was determined by multiplying the PCSA by the cosine of the resting vastus lateralis fascicle θ_p, where fascicle θ_p

was representative of the mean quadriceps femoris fascicle θ_p [5]. Subsequently, dividing knee extension corrected iMVC torque by the patellar tendon moment arm (0.048 m) previously reported for healthy young men provided maximum isometric knee extensor force. Quadriceps femoris specific force was calculated as maximum isometric knee extensor force divided by reduced PCSA [5].

Statistical analyses

The mean and standard deviation (*s*) were calculated for all variables. All data were tested for normality using the Shapiro Wilks normality test. For variables measured at three different time points during explosive isometric contractions (force, RFD, RFD relative to isometric maximal voluntary force), the influence of group and time interval was analysed with a mixed repeated measures ANOVA (two groups x three time intervals). All other dependent variables were assessed using an independent samples *t*-test. Pearson's correlations were used to determine relations between jump performance variables [height or projectile range, peak V-power, peak horizontal power or peak medial power and muscle size, morphology and activation. Statistical analysis was completed using SPSS version 23 (SPSS Inc., Chicago, IL), and the significance level was set at $P \leq 0.05$.

RESULTS

Differences between elite and non-elite soccer players

Muscle Strength

Differences between elite and non-elite soccer players for muscle strength, muscle size and architecture, and voluntary muscle activation are presented in Tables 1, 2 and 3, respectively.

Insert Table 1 here

Insert Table 2 here

Insert Table 3 here

The neuromuscular factors contributing to unilateral direction-specific jump performance

The positive and inverse relationships between jump performance variables and neuromuscular factors are displayed in Table 4. Additional figures have been included to illustrate the spread of data for specific relationships.

Both groups

Unilateral vertical CMJ peak V-power correlated with quadriceps femoris M_{vol} (Fig. 1A), relative quadriceps femoris M_{vol}, PCSA and vastus lateralis muscle thickness (Table 4). No performance measure of unilateral horizontal-forward CMJ correlated with any measure of muscle size or vastus lateralis architecture ($P \geq 0.066$). However, unilateral medial CMJ peak V-power correlated with quadriceps femoris M_{vol} (Fig. 1B), relative quadriceps femoris M_{vol}, quadriceps femoris PCSA and mean vastus lateralis activation in the upward phase (Table 4).

Insert Figure 1 here

Elite Group Only

Unilateral vertical CMJ peak V-power correlated significantly with PCSA (r = 0.550, P = 0.010), quadriceps femoris M_{vol} (r = 0.508, P = 0.019) and relative quadriceps femoris M_{vol} (r

= 0.500, P = 0.021). Unilateral vertical CMJ height correlated significantly with mean upward phase vastus lateralis activation (Table 4) and vastus lateralis θ_p (Fig. 2A). Similarly, unilateral medial CMJ peak V-power correlated significantly with mean upward phase vastus lateralis activation (r = 0.471, P = 0.042) and unilateral medial CMJ projectile range correlated significantly with vastus lateralis θ_p (Fig. 2C). In contrast, unilateral horizontal-forward CMJ peak V-power correlated inversely with vastus lateralis θ_p (Fig. 2B).

Insert Figure 2 here

Non-elite Group Only

Unilateral vertical CMJ peak V-power correlated with quadriceps femoris M_{vol} (r = 0.492, P = 0.028). Unilateral horizontal CMJ peak V-power correlated significantly with relative L_f (Table 4). Unilateral medial CMJ peak V-power correlated inversely with mean vastus lateralis activation in the downward phase (Table 4).

Insert Table 4 here

DISCUSSION

The aims of our study were to investigate the differences in neuromuscular characteristics between elite and non-elite soccer players, and determine which neuromuscular factors contributed to unilateral CMJ performance in different directions. We have shown for the first time that elite soccer players presented with greater knee extensor iMVT, quadriceps femoris M_{vol} (absolute and relative to femur length), and quadriceps femoris PCSA than non-elite soccer players. Correlations between jump performance variables and neuromuscular factors in both cohorts revealed that absolute and relative quadriceps femoris M_{vol}, and PCSA contribute to unilateral vertical and medial, but not horizontal-forward CMJ performance. In elite soccer players only, vastus lateralis θ_p correlated positively with unilateral vertical and medial, but inversely with horizontal-forward CMJ performance. Moreover, vastus lateralis activation during the upward CMJ phase correlated only with unilateral vertical CMJ height and unilateral medial CMJ peak V-power in elite soccer players. Our data shows that quadriceps femoris muscle size (M_{vol} and PCSA) and maximal isometric force may be characteristics of elite soccer playing status; and the neuromuscular factors underpinning unilateral CMJ performance are direction-specific, with a different combination of neuromuscular factors underpinning unilateral vertical and medial, compared to horizontal-forward CMJ performance.

It is imperative that physiological assessments for elite soccer players evaluate characteristics considered important for high-level soccer performance. If the presentation of performance or physiological factors differ between elite and non-elite soccer players, these characteristics may be important for performance at the elite level [23,24] and could therefore be considered within soccer talent identification criteria. Within this context, elite soccer players presented with greater knee extensor iMVT but similar knee flexor iMVT and knee extensor isometric explosive capabilities, compared to non-elite soccer players. Previous research has shown differences between elite and amateur players in knee flexor isokinetic strength [23] but the current results are the first to suggest that knee extensor isometric strength may be an indicator of elite soccer playing status. Elite soccer players presented with significantly greater absolute and relative quadriceps femoris M_{vol}, and quadriceps femoris PCSA than non-elite soccer players. However, vastus lateralis architecture and muscle specific force (maximum force per unit PCSA) were not different between groups, thus suggesting that muscle quality is similar between elite and non-elite soccer players. As 12 weeks of recreational soccer training has been shown to result in a 12% increase in muscle fibre cross sectional area in untrained participants [25], it is possible that the greater QF size in ESP could be attributed to them performing high force muscle actions more frequently during professional soccer training (as opposed to non-elite soccer players, who performed soccer training less regularly). Alternatively, as QF M_{vol}, strength and power in healthy young men are associated with a variation of the alpha-actinin-3 *(ACTN3)* gene [26], and elite soccer players have previously been shown to have a higher frequency of the preferential *ACTN3*genotype compared to endurance athletes and control participants [27], it is possible that the differences reported here in QF muscle morphology between elite and non-elite soccer players are associated with differences in genetic make-up. Whilst further research is needed to test these hypotheses, we are the first to show that knee extensor iMVT and quadriceps femoris muscle size differentiate between elite and non-elite soccer players.

Investigating the physiological mechanisms that underpin soccer performance characteristics can inform the specific detail of performance enhancement programmes. Quadriceps femoris muscle size (M_{vol} and PCSA) was related to unilateral vertical and medial CMJ peak V-power, but not to any measure of unilateral horizontal-forward CMJ performance in elite and non-elite soccer players. These findings are somewhat in accordance with previous research that reported a positive relationship between bilateral vertical CMJ and quadriceps femoris muscle volume [6,7]. Horizontal-forward CMJs have previously been shown to require greater hamstring activation [13,14], and a greater motion and more vigorous utilization of the hip joint [13,14] than vertical CMJs. Therefore, it may be that properties of the hamstring muscle group, rather than the quadriceps femoris, determine unilateral horizontal-forward CMJ performance. Vertical CMJs, on the other hand, produce greater knee joint moments [13,14]. Therefore, larger PCSA and M_{vol} of the quadriceps femoris muscle group appear to be more important for unilateral vertical CMJ peak V-power production. The positive effect of a large quadriceps femoris muscle group on unilateral medial CMJ performance may also suggest that unilateral medial CMJs require high moments at the knee joint, although this has not yet been investigated. Our data suggest that the greater quadriceps femoris M_{vol} displayed by the elite soccer players could be advantageous for soccer performance by facilitating explosive unilateral propulsive movements directed in the vertical and medial, but not horizontal, directions. Moreover, as it has previously been reported that elite soccer players are required to perform approximately 50 forceful changes of direction [28], and many other unorthodox powerful movements while exerting physical force against an opponent [29], it is also possible that the greater quadriceps femoris muscle size and strength (displayed by elite players), may assist to stabilise the knee during such explosive actions.

In addition to muscle size, the architecture of the muscle is thought to be important in determining the power output of the whole muscle [12,30]. The vastus lateralis θ_p measurements in soccer players in the current study were similar to values previously reported in youth elite soccer players [31]. The current study is the first to show that vastus lateralis θ_p was positively related to unilateral vertical CMJ height and unilateral medial CMJ peak V-power, but was inversely related to unilateral horizontal-forward CMJ peak V-power in elite soccer players. Presuming the geometry of the vastus lateralis is representative of the total quadriceps femoris muscle architecture [5], the greater vastus lateralis θ_p and in theory, greater number of sarcomeres aligned in parallel (and therefore, greater PCSA) [9,32], could allow the quadriceps femoris muscle to extend the knee joint with more force (and therefore, power) [32], thus increasing unilateral vertical and unilateral medial CMJ performance in elite soccer players. However, greater θ_p has been associated with reduced muscle contraction velocity [9,12] and RFD [11]. As the unilateral horizontal-forward CMJ requires greater take-off velocities than unilateral vertical and unilateral medial CMJs, a greater vastus lateralis θ_p may reduce the quadriceps femoris contraction velocity and therefore, reduce peak V-power during unilateral horizontal-forward propulsion. Hence, we have demonstrated that the contribution of quadriceps femoris muscle architecture to unilateral CMJ performance in soccer players is specific to the direction of the jump. Nevertheless, it should be noted that our study was limited as we only measured the geometry of the vastus lateralis muscle and assumed it representative of the total quadriceps femoris muscle.

Maximal power production is not only governed by muscle size and architecture, but by the ability of the nervous system to activate the specific muscle groups during ballistic actions [4]. Mean upward phase vastus lateralis activation was positively related to vertical (unilateral vertical CMJ height) and medial (unilateral medial CMJ peak V-power) jump performance in elite soccer players. However, downward phase vastus lateralis activation was inversely related to unilateral medial CMJ peak V-power in non-elite soccer players. Previous research has documented a strong relationship between bilateral vertical CMJ performance and knee extensor muscle activation during the first 100 ms of the rise in ground reaction force ($r = 0.81$) [33], and a moderate relationship between bilateral vertical CMJ and drop jump peak concentric force, and downward phase vastus lateralis activation ($r = 0.599$) [34]. These studies support our findings with the elite, but are in contrast to our findings in non-elite, soccer players. There were no relationships between unilateral horizontal-forward CMJ performance and vastus lateralis activation or biceps femoris activation in either cohort. Our study demonstrates that biceps femoris activation does not contribute to unilateral CMJ performance in different directions. However, greater vastus lateralis activation enhances unilateral vertical and unilateral medial, but not unilateral horizontal-forward CMJ performance, in elite soccer players.

PRACTICAL APPLICATIONS

Our data suggest that elite soccer clubs could include knee extensor iMVC torque and quadriceps femoris size (M_{vol} and PCSA) assessments in novel talent selection criteria.

Moreover, when aiming to develop unilateral vertical and medial jump capabilities, elite soccer players should focus on increasing quadriceps femoris size (volume and PCSA) and vastus lateralis pennation angle. In contrast, increasing vastus lateralis pennation angle may have a negative impact upon unilateral horizontal-forward CMJ capabilities and therefore, training methods for developing unilateral power performance should target neuromuscular adaptations specific to the direction of the jump.

CONCLUSION

By comparing neuromuscular characteristics in elite and non-elite soccer players, we have demonstrated that greater knee extensor iMVC torque and quadriceps femoris size (M_{vol} and PCSA) may be important indicators of elite soccer playing status. Moreover, we show that the size of the quadriceps femoris muscle group contributes to unilateral vertical and unilateral medial CMJ, but not unilateral horizontal-forward CMJ performance. We also propose that the greater knee extensor iMVC torque and quadriceps femoris size (M_{vol} and PCSA) displayed by elite soccer players could also assist in stabilising the knee during explosive change of direction tasks performed during soccer match-play. In elite soccer players, greater vastus lateralis muscle activation and vastus lateralis fascicle pennation angle appear to enhance CMJ performance in the vertical and medial directions, but a larger vastus lateralis pennation angle reduces unilateral horizontal-forward CMJ performance. Together these findings suggest that jump performance in the vertical and medial directions are underpinned by similar neuromuscular characteristics, which are in contrast to the unilateral horizontal-forward CMJ.

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Tables

TABLE 1. Measured and calculated isometric contraction variables in elite (n = 23) and non-elite (n = 20) players; mean ± SD.

Variable	Elite	Non-elite
KE iMVT (N·m)	365.7 ± 66.6*	320.1 ± 62.6
KF iMVT (N·m)	121.2 ± 39.5	116.3 ± 22.1
Co-activation (%)	27.9 ± 13.5	23.7 ± 15.6
Specific force ($N \cdot cm^{-2}$)	36.8 ± 7.3	36.5 ± 8.7
Peak RFD ($N \cdot s^{-1}$)	48,284 ± 11,689	43,045 ± 9,110
Time to peak RFD (ms)	72 ± 16	68 ± 16
RFD 0-50 ms ($N \cdot s^{-1}$)	14,812 ± 10,113	13,666 ± 6,239
RFD 50-100 ms ($N \cdot s^{-1}$)	30,226 ± 9,486	28,554 ± 7,694
RFD 100-150 ms ($N \cdot s^{-1}$)	22,394 ± 7,343	20,325 ± 5,644
nRFD 0-50 ms ($\%MVF \cdot s^{-1}$)	2.236 ± 1.582	2.286 ± 1.176
nRFD 50-100 ms ($\%MVF \cdot s^{-1}$)	4.622 ± 1.148	4.590 ± 1.195
nRFD 100-150 ms ($\%MVF \cdot s^{-1}$)	3.374 ± 0.608	3.212 ± 0.659

KE, knee extensor; iMVT, isometric maximal voluntary torque; RFD, rate of force development; nRFD, rate of force development normalised to maximum voluntary force (MVF).

* Elite significantly greater than non-elite ($P < 0.05$)

TABLE 2. Quadriceps femoris (QF) muscle morphology and architecture in elite (n=23) and non-elite (n=20) players; mean ± SD.

Muscle variable	**Elite**	**Non-Elite**
QF V_m (cm^3)	2852.5 ± 507.5**	2428.8 ± 232.1
Relative QF V_m (cm^3/cm)	61.06 ± 9.45*	54.67 ± 4.06
QF PSCA (cm^2)	227.16 ± 42.31*	192.57 ± 25.42
QF ACSA (cm^2)	80.85 ± 15.84*	69.80 ± 6.72
VL muscle thickness (mm^2)	26.41 ± 2.93	26.06 ± 3.25
VL θ_p (°)	14.88 ± 2.23	14.65 ± 2.04
VL L_f (mm)	127.20 ± 18.11	127.84 ± 17.43
Relative VL L_f (mm/cm)	2.73 ± 0.40	2.88 ± 0.37

V_m, muscle volume; PCSA, physiological cross-sectional area; ACSA, anatomical cross-sectional area; VL, vastus lateralis muscle; θ_p, angle of pennation; L_f, fascicle length.

* Significantly greater than non-elite ($P < 0.01$)

** Significantly greater than non-elite ($P \leq 0.001$)

TABLE 3. Peak muscle activation (% iMVC) attained during direction-specific unilateral countermovement jumps (CMJs) in elite (n=19) and non-elite (n=19) players; mean ± SD.

		Peak VL EMG (%iMVC)		**Peak BF EMG (%iMVC)**	
CMJ	**Jump Phase**	**Elite**	**Non-Elite**	**Elite**	**Non-Elite**
UV	Downward	106.5 ± 70.4	105.2 ± 39.8	47.6 ± 19.6	60.5 ± 36.1
	Upward	227.4 ± 134.5	156.6 ± 78.3	91.3 ± 46.2	87.1 ± 45.6
UH	Downward	139.1 ± 67.9	103.6 ± 35.4	118.0 ± 43.3	124.3 ± 66.3
	Upward	190.5 ± 100.3	143.1 ± 37.3	125.7 ± 68.7	128.6 ± 51.0
UM	Downward	107.8 ± 65.1	104.0 ± 35.9	44.5 ± 36.5	54.9 ± 20.1
	Upward	183.5 ± 101.2	140.7 ± 33.4	87.3 ± 68.7	73.7 ± 35.9

VL, vastus lateralis muscle; EMG, electromyography; iMVC, isometric maximal voluntary contraction; UV CMJ, unilateral vertical countermovement jump; UH CMJ, unilateral horizontal-forward countermovement jump; UM CMJ, unilateral medial countermovement jump.

Table 4. Correlations between unilateral countermovement jump (CMJ) performance measures and neuromuscular properties of the quadriceps femoris muscle group in elite (n = 23) and non-elite (n = 20) soccer players. Inverse correlations are highlighted in **bold**.

	Jump type							
	Unilateral vertical CMJ		**Unilateral horizontal-forward CMJ**			**Unilateral medial CMJ**		
Neuromuscular variable	Jump height (cm)	Peak V power (W/kg)	Projectile range (cm)	Peak H-power (W/kg)	Peak V-power (W/kg)	Projectile range (cm)	Peak M-power (W/kg)	Peak V-power (W/kg)
QF V_m (cm^3)		Fig. 1						Fig. 1
QF V_m relative to FL (cm^3/cm)		$r = 0.539$ $P < 0.001$						$r = 0.389$, $P = 0.01$
QF PSCA (cm^2)		$r = 0.524$ $P < 0.001$						$r = 0.310$ $P = 0.043$
VL muscle thickness (mm^2)		$r = 0.323$ $P = 0.039$						
VL θ_p (°)	Fig. 2				Fig. 2	Fig. 2		
Relative VL L_f (mm/cm)					r = 0.482 [b] $P = 0.031$			
VL EMG upward phase	$r = 0.498$ [a] $P = 0.042$							$r = 0.346$, $P = 0.039$
VL EMG downward phase								$\boldsymbol{r = -0.532}$ **[b]** $\boldsymbol{P = 0.034}$

V_m, muscle volume; FL, femur length; PCSA, physiological cross-sectional area; ACSA, anatomical cross-sectional area; MT, muscle thickness; VL, vastus lateralis muscle; θ_p, angle of pennation; L_f, fascicle length.

[a] Significantly correlation in elite players only

Figure Legends

Figure 1. The relationships between: unilateral vertical countermovement jump (CMJ) peak V-power and quadriceps femoris muscle volume (Mvol) (a; $r = 0.566$, $P < 0.001$); unilateral medial CMJ peak V-power and quadriceps femoris Mvol (b; $r = 0.438$, $P = 0.003$) in elite ($n = 23$) and non-elite ($n = 20$) players. Peak V-power, peak vertical power allometrically scaled to body mass.

Figure 2. The relationships between vastus lateralis pennation angle (p) and: unilateral vertical countermovement jump (CMJ) height (a; $r = 0.478$, $P = 0.028$); unilateral horizontal-forward CMJ peak V-power (b; $r = -0.437$, $P = 0.037$); unilateral medial CMJ projectile range (c; $r = 0.413$, $P = 0.050$) in elite players ($n = 23$). Peak V-power, peak vertical power allometrically scaled to body mass.

Figure 1

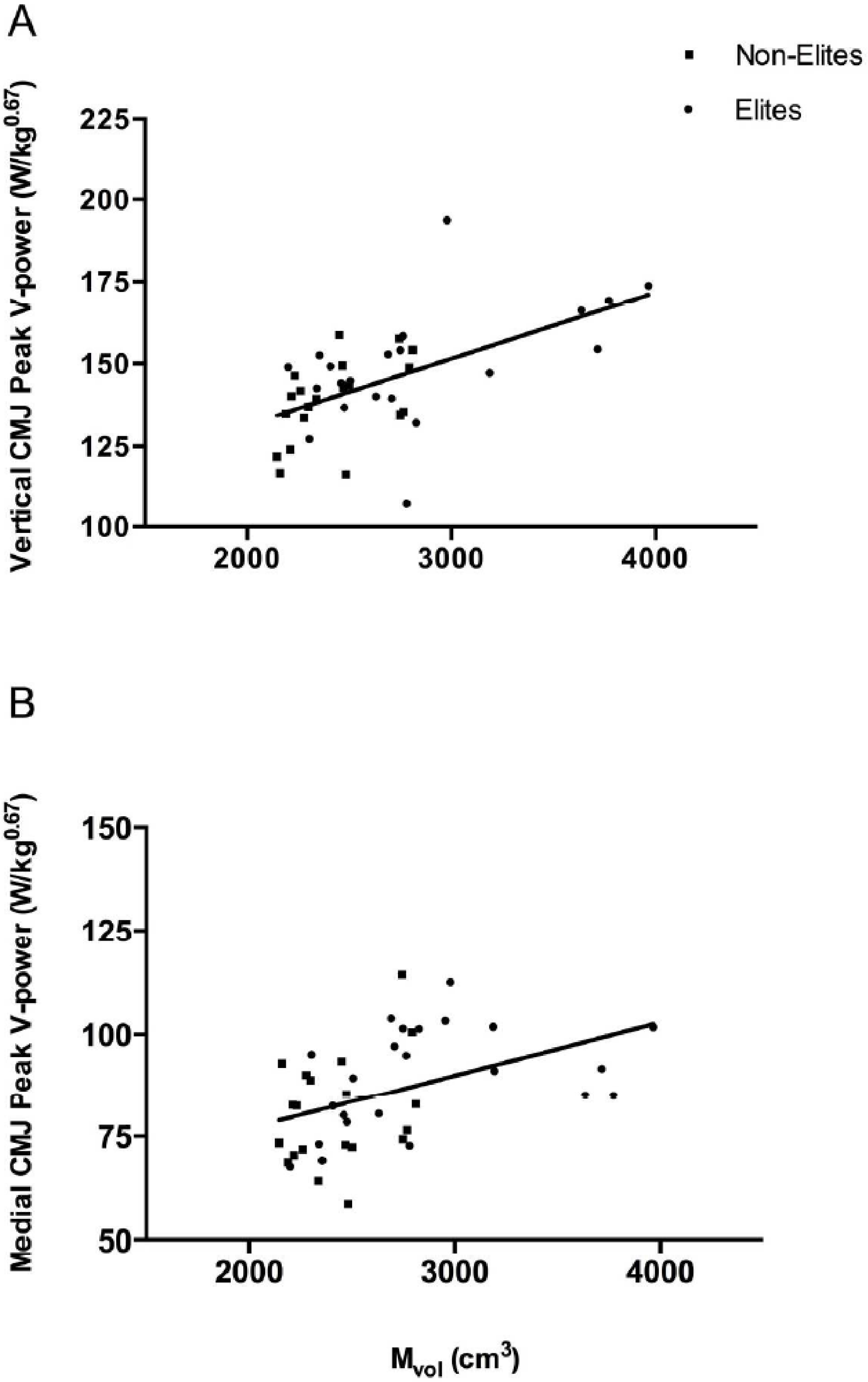
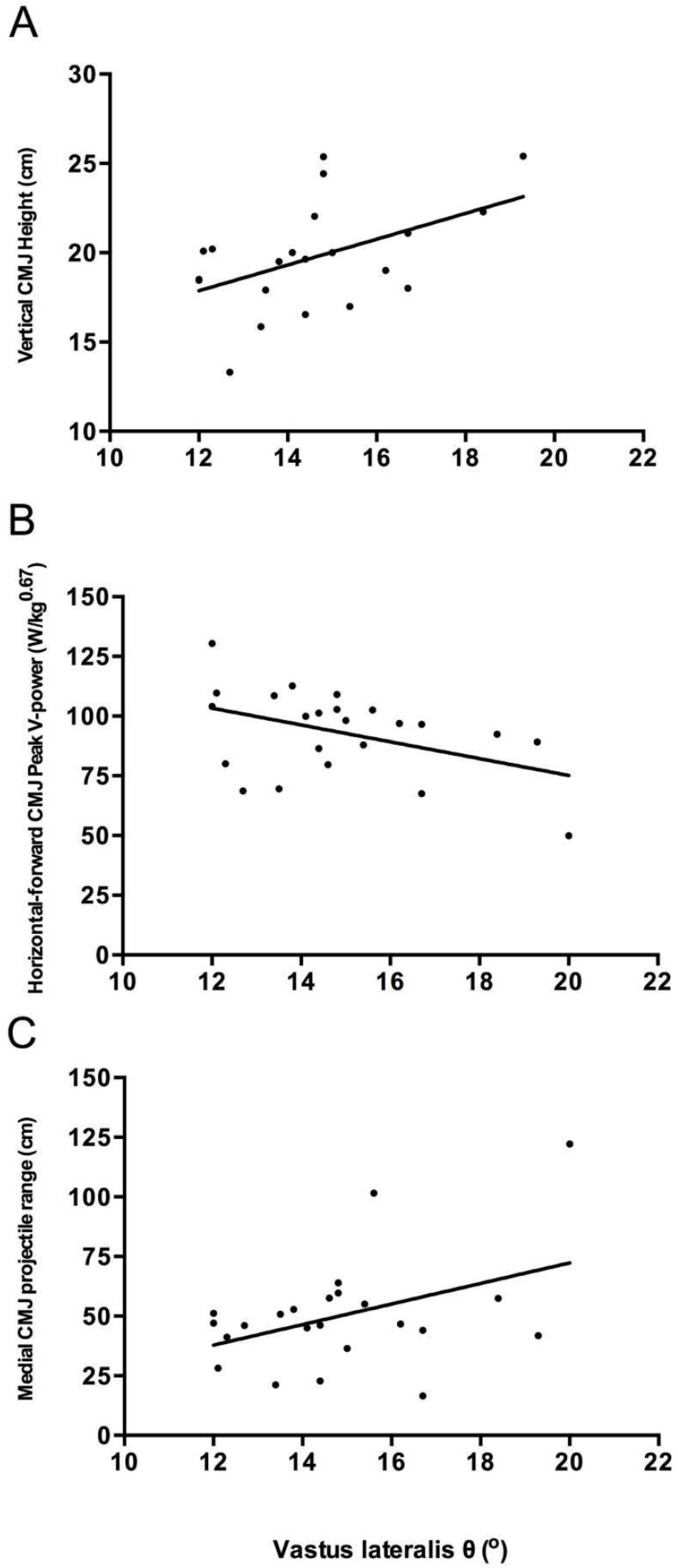

A
Non-Elites
Elites
Vertical CMJ Peak V-power (W/kg$^{0.67}$)
225
200
175
150
125
100
2000
3000
4000
B
Medial CMJ Peak V-power (W/kg$^{0.67}$)
150
125
100
75
50
2000
3000
4000
M_{vol} (cm^3)

Figure 2


A
30
25
20
15
10
Vertical CMJ Height (cm)
10
12
14
16
18
20
22
B
150
125
100
75
50
25
0
Horizontal-forward CMJ Peak V-power (W/kg0.67)
10
12
14
16
18
20
22
C
150
125
100
75
50
25
0
Medial CMJ projectile range (cm)
10
12
14
16
18
20
22
Vastus lateralis θ (°)